

SEMIANNUAL STATUS REPORT



MODELING OF TRANSIENT HEAT PIPE OPERATION

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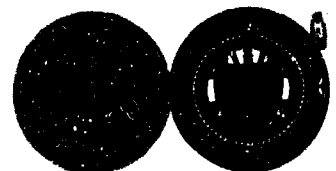
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MODELING OF TRANSIENT HEAT PIPE OPERATION

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INTRODUCTION

The major goal of this project is to develop mathematical models of heat pipes which can be used to predict transient behavior under normal and adverse conditions. The models and solution techniques are to be formulated so that they can be incorporated into existing NASA structural design codes. The major parameters of interest are heat flux distribution, temperature distribution, working fluid pressure distribution, fluid and containment thermal and mechanical properties and geometry. Normal transient operation is taken to be operating conditions where the capillary structure remains fully wetted. Adverse transient operation occurs when drying, re-wetting, choking, non-continuum flow, thawing, freezing, etc., occur in the internal heat pipe working fluid.

The models and solution techniques developed under this grant will be directed primarily towards the types of heat pipes which may be used in the "Space Station" for moving large quantities of thermal energy and for heating and cooling of instruments. However, with some modifications, the resulting models could be used for designing and predicting performance of high temperature heat pipes of the type proposed for cooling airframe and engine components in hypersonic applications such as the "Scramjet" and the "Shuttle".

Another goal of this project is to supply to NASA on a continuing basis throughout the grant period, information needed to determine sizes and weights of various types of heat pipes that may be proposed by others for "Space Station" use.

PROGRAM WORK STATEMENT

The program will require about three years to complete. The following steps will be taken to accomplish the work.

- i. Compile governing transient equations for normal heat pipe operation.
- ii. Model adverse conditions and select non-dimensional groups which can be used to define regimes where adverse operation occurs.
- iii. Incorporate models for adverse operations into solution techniques. This will involve using thermal property subroutines to predict properties for use in conduction equations.
- iv. Assess adequacy of existing finite element computational schemes to handle the models developed.
- v. Develop finite element representation of heat pipe for normal operation.
- vi. Include non-dimensional groups which define adverse operating regimes in computational scheme.
- vii. Select test case to demonstrate techniques.
- viii. Compute operating parameters for test case.
- ix. Test computed values against experimental results for test case.
- x. Perform parametric studies for systems to the extent possible.
- xi. Develop, to the extent possible with given time and resources, simplified correlation equations or design procedures.

- xii. Integrate the results of the above steps into existing finite element stress computation programs.

It is anticipated that the work included in tasks i, ii and iii and part of the work in task iv will be completed during the currently funded grant. The second year of work will be needed to carry out tasks v through viii and the third year should allow completion of the remaining tasks.

PROGRESS TO DATE

The work to date has been mainly directed towards defining the program, planning the steps required to achieve the desired final result and in formulating very general governing equations for normal heat pipe operation. This activity falls under task i of the program work statement. The following brief summary gives the current approach to the modeling.

FINITE ELEMENT MODELING OF NORMAL TRANSIENT

HEAT PIPE OPERATION

Under normal transient operation a heat pipe easily accommodates external changes in the heat loads at the evaporator or condenser sections. While the internal temperatures and pressures vary as the heat pipe reacts to the external changes, the capillary structure remains fully wetted and the temperature and pressure in the vapor region are nearly uniform across any cross-section at an instant of time. Thus, for normal transient operation, the following assumptions [1] are usually made:

1. Heat is transferred through the shell of the heat pipe and through the liquid-saturated circumferential capillary structure by conduction only;
2. Thermal resistances associated with vaporization and condensation along the interface between the vapor region and the capillary structure are negligible; and

3. The temperature in the vapor space may change with time and position (along the length of the heat pipe) but is uniform across any cross-section normal to the axial direction

The mathematical description of the heat transfer in a cylindrical heat pipe for these conditions can be written as follows:

$$(\rho c)_i \frac{\partial T_i}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (k_i r \frac{\partial T_i}{\partial r}) + \frac{\partial}{\partial z} (k_i \frac{\partial T_i}{\partial z}), \quad i = 1, 2 \quad (1)$$

where the subscripts 1 and 2 denote the heat pipe shell and the liquid-saturated circumferential capillary, respectively. The effective thermal conductivity of the liquid filled circumferential structure may be computed from expressions such as that developed by Williams [2].

The volumetric specific heat of the capillary (ρc) , is a mass-averaged value to account for the presence of liquid. For the vapor regions, subscript 3, the energy equation is written as

$$(\rho c)_3 \frac{\partial T_3}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (k_{r3} \frac{\partial T_3}{\partial r}) + \frac{\partial}{\partial z} (k_{z3} \frac{\partial T_3}{\partial z}) \quad (2)$$

In order to satisfy assumption (3) above, the thermal conductivity in the radial direction, k_{r3} , can be chosen such that

$$\frac{k_{r3}}{(\rho c)_3} \gg 1$$

The effective thermal conductivity in the axial direction, k_{z3} , is evaluated by solving momentum and energy equations in the vapor region. Plesset and

Poesperetti [3] discuss conditions in this region in a very general manner.

The boundary conditions for this formulation consist of the following:

1. At each interface between the three regions, the temperature and the heat flux are continuous. Thus, in the evaporator and condenser sections

$$\begin{array}{l} \text{and} \\ k_1 \frac{\partial T_1}{\partial r} = k_2 \frac{\partial T_2}{\partial r} \\ T_1 = T_2 \end{array} \left. \vphantom{\begin{array}{l} \text{and} \\ k_1 \frac{\partial T_1}{\partial r} = k_2 \frac{\partial T_2}{\partial r} \\ T_1 = T_2 \end{array}} \right\} \begin{array}{l} \text{at } r = r \\ \text{and } 0 < z < L_e \\ L - L_c < z < L \end{array} \begin{array}{l} \text{(interface} \\ \text{between shell} \\ \text{and capillary)} \end{array}$$

$$\begin{array}{l} \text{and} \\ k_2 \frac{\partial T_2}{\partial r} = k_{r3} \frac{\partial T_3}{\partial r} \\ T_2 = T_3 \end{array} \left. \vphantom{\begin{array}{l} \text{and} \\ k_2 \frac{\partial T_2}{\partial r} = k_{r3} \frac{\partial T_3}{\partial r} \\ T_2 = T_3 \end{array}} \right\} \begin{array}{l} \text{at } r = r_2 \\ \text{and } 0 < z < L_e \\ L - L_c < z < L \end{array} \begin{array}{l} \text{(interface} \\ \text{between} \\ \text{capillary and} \\ \text{vapor region)} \end{array}$$

and in the adiabatic section

$$\begin{array}{l} \text{and} \\ k_1 \frac{\partial T_1}{\partial r} = k_{r3} \frac{\partial T_3}{\partial r} \\ T_1 = T_3 \end{array} \left. \vphantom{\begin{array}{l} \text{and} \\ k_1 \frac{\partial T_1}{\partial r} = k_{r3} \frac{\partial T_3}{\partial r} \\ T_1 = T_3 \end{array}} \right\} \begin{array}{l} \text{at } r = r_1 \\ \text{and} \\ L_e < z < L - L_c \end{array}$$

In a relatively long heat pipe with energy added and removed radially along the length energy transfer through the ends may be neglected. In those cases where end effects are significant they may be easily included in the model.

2. For the cylindrical heat pipe under consideration there is radial symmetry about the axis of the pipe,

$$\frac{\partial T_3}{\partial r} = 0 \text{ at } r = 0 \text{ (centerline)} \\ \text{and } 0 < z < L_p$$

3. No heat transfer occurs external to the shell at the adiabatic section,

$$\frac{\partial T_1}{\partial r} = 0 \text{ at } r = r_o \text{ (outer radius of shell)} \\ \text{and } L_e < z < L - L_c$$

4. The external surface of the shell at the evaporator and condenser sections can be exposed to a uniform heat flux, conduction, convection, or radiation. Thus,

$$-k_1 \frac{\partial T_1}{\partial r} = h(T_1 - T_\infty) + \sigma F(T_1^4 - T_\infty^4) - q''$$

or

$$k_1 \frac{\partial T_1}{\partial r} = k_2 \frac{\partial T_2}{\partial r} \text{ at } r = r_o \text{ and } 0 < z < L_e \\ L - L_c < z < L$$

where k_s is the conductivity of the surrounding material and $\frac{\partial T_s}{\partial r}$ is the gradient in that material at r_o . The initial condition for the analysis of normal transient operation may be taken to be the steady-state solution at design conditions or some other prescribed state.

Existing finite element codes which have the capability of solving transient condition problems can be modified so that normal transient heat pipe operation, as formulated above, can be treated. The finite element formulation must allow for element property variations with time as well as from element to element. Furthermore, provision must be made for treating anisotropic elements since the thermal conductivity of elements in the vapor region is different in the radial and axial directions.

Property subroutines must be developed in order to evaluate the thermal properties as a function of temperature for elements which represent the heat pipe components and the working fluid. These subroutines are presently being developed at Georgia Tech and will be incorporated into an existing finite element code. The normal transient heat pipe model in finite element form will be incorporated initially into a finite element codes developed in the School of Mechanical Engineering at Georgia Tech in 1978. This is a two-dimensional, transient program which is capable of treating three-dimensional problems having radial symmetry such as exists in the present heat pipe formulation. Simple, three-node triangular elements are used in this code, but the proposed implementation is not limited to low-order interpolation functions. The property subroutines described above will be added to this existing finite element code to demonstrate the validity of the finite element implementation. Validation will consist of comparing numerical solutions with available experimental data from normal transient heat pipe tests.

For other than normal transient operation, additional capabilities must be added to existing codes in order to model phenomena such as dryout and rewetting of the capillary wick structure as well as melting or freezing of the working fluid. At present, we believe that these phenomena can adequately be treated by means of modification and additions to the thermal property

subroutines. The major efforts associated with these task consist of developing accurate analytical models of the phenomena and numerical algorithms suitable for finite element solutions.

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